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The relativistic solar proton event of 6 November 1997 resulted in the first ground-level enhancement (GLE) of solar cycle 23. The earliest onset was around 1215 UT but was up to 15 minutes later at some neutron monitor locations. The time of maximum intensity also varied significantly over the world-wide neutron monitor network. The modeled particle distributions and spectra are presented. The apparent particle arrival direction is found to be largely consistent with propagation outward from the sun along interplanetary magnetic field lines.

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THE COSMIC RAY GROUND LEVEL ENHANCEMENT OF 6 NOVEMBER 1997

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ABSTRACT

The relativistic solar proton event of 6 November 1997 resulted in the first ground-level enhancement (GLE) of solar cycle 23. The earliest onset was around 1215 UT but was up to 15 minutes later at some neutron monitor locations. The time of maximum intensity also varied significantly over the world-wide neutron monitor network. The modeled particle distributions and spectra are presented. The apparent particle arrival direction is found to be largely consistent with propagation outward from the sun along interplanetary magnetic field lines.

INTRODUCTION

The first solar cosmic ray GLE (ground level enhancement) of the 23rd solar cycle occurred on 6 November 1997 and was recorded by at least 16 neutron monitors with geomagnetic cutoffs up to $\sim$3.5 GV. The earliest onset was in the five-minute interval 1215-1220 UT as was concluded from the recordings of several stations including Climax, USA, Goose Bay, Canada and South Pole, Antarctica. A maximum amplitude of 17.7% was recorded at South Pole at 1354–55 UT.

A 2B/X9.4 solar flare at heliocentric coordinates 18° S, 63° W in active region 8100 is believed associated with this solar particle event. The Hα onset occurred at 1149 UT, and the maximum Hα intensity was observed at 1155 UT. Concurrent type II and type IV radio emission was also recorded (Solar-Geophysical Data, 1997, 1998). In addition, a coincident fast coronal mass ejection (CME) was identified by the LASCO instrument on the SOHO spacecraft.

In our technique for modelling neutron monitor responses to solar particle events (Cramp et al., 1997), we employ the Tsyganenko (1989) geomagnetic field models to determine the asymptotic viewing directions of ground-based instruments (Flückiger and Kobel, 1990). A least-squares fitting technique minimizing the difference between the computed and measured response for each neutron monitor is used to determine the apparent particle arrival direction, pitch angle distribution and rigidity spectrum. In addition to accurately representing the observed cosmic ray increases, the model should produce null responses for those stations which did not record any intensity increase. Thus, it is important to include stations at many different geographic locations so that a wide range of viewing directions and cutoff rigidities will be included in the analysis.

Five-minute average data from 17 neutron monitors were modeled in this analysis. The observed increases were corrected to sea level atmospheric pressure by the two-attenuation length method (McCracken, 1962) using an attenuation length of 100 g cm^{-1}. An exponential form was used for the pitch angle distribution, and the spectra were modeled as power laws in rigidity.

RESULTS AND DISCUSSION

Ground-level neutron monitor responses were modeled for 11 five-minute intervals between 1230 and 1500 UT. Figure 1 shows the observed increases at 16 stations between 1215-1515 UT. Modeled points are indicated by error bars. Calculated increases are also shown. The modeling procedure

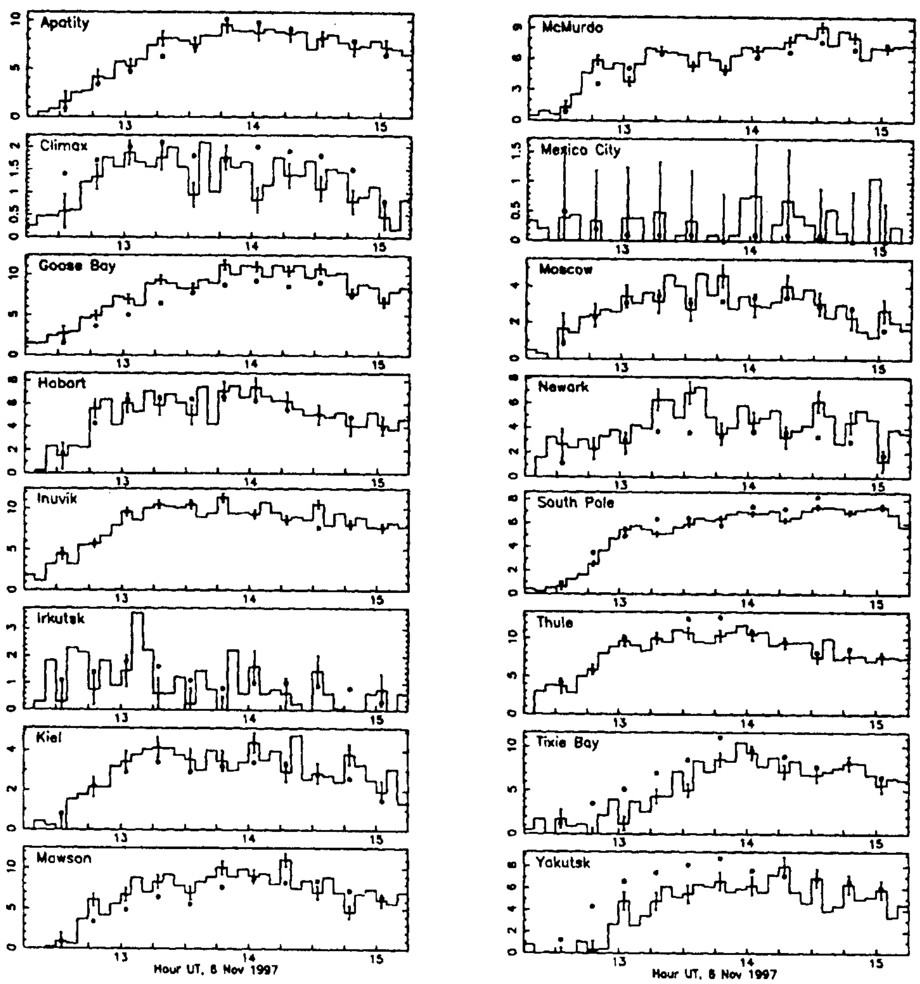

Fig. 1. Five-minute average neutron monitor data between 1215 and 1515 UT. The calculated increases are shown as dots. The modeled points are indicated by the error bars. Data from Mt. Wellington, Australia were also used in this analysis but are not shown here.

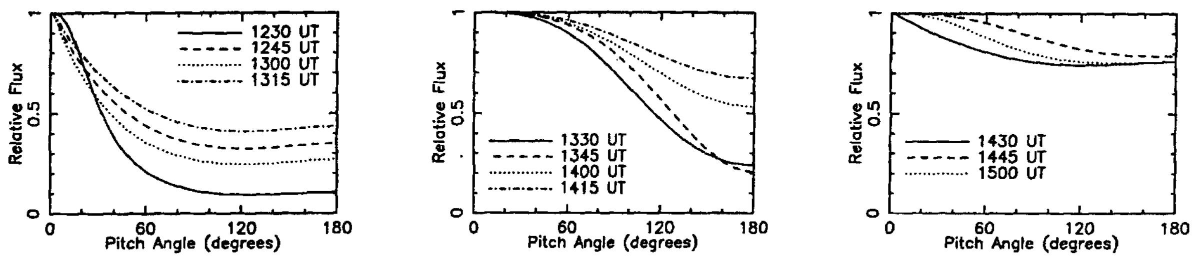

Fig. 2. The modeled pitch angle distributions.

requires that one station be used for normalisation to allow determination of the spectral constant. This station was chosen to be Inuvik for all times except 1430-35 UT when we used Apatity.

Neutron monitor observations indicate that particles with rigidities up to ~4 GV were associated with this enhancement. Figure 2 shows that the particle flux distribution was initially mildly anisotropic with the degree of anisotropy gradually decreasing. The derived rigidity spectra are shown in Figure 3 except for the interval 1230-1235 UT. Observations at this time are consistent with a spectrum with power law exponent of ~–5, but the uncertainty in the modeled spectrum is large due to the lack of data from mid-latitude stations viewing near the particle arrival direction. The large uncertainty in the spectrum results in slightly greater uncertainties in the derived pitch angle distribution and particle arrival direction than at later times. The spectrum softened during the event and by 1500-1505 UT the power law exponent was –7.5.

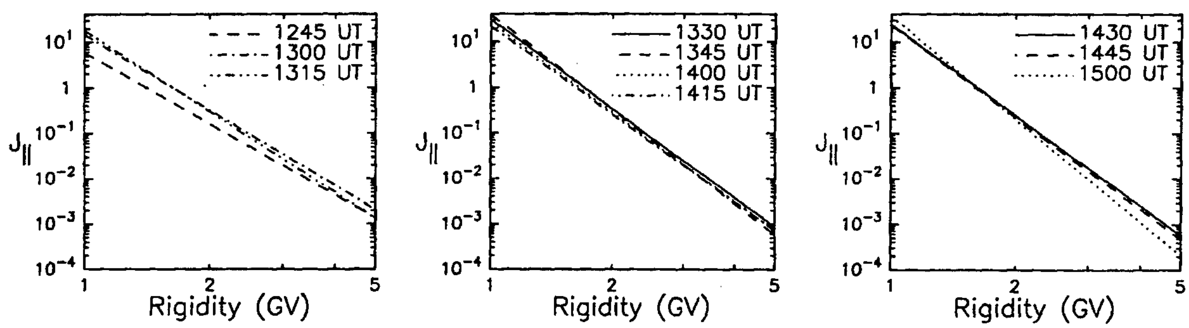

Fig. 3. The modeled differential rigidity spectra. Flux units are $(cm^2\ s\ GV)^{-1}$

During the time interval of this ground-level solar particle event the measured interplanetary magnetic field (IMF) direction was very variable. A CME from the 4 November 1989 event was approaching Earth, passing the earth at about 1800 UT on 6 November. This approaching CME apparently had no discernible effect on the high energy particle flux.

Figure 4 displays the derived particle arrival directions (axes of symmetry of the pitch angle distributions) and the IMF direction measured by the earth-orbiting IMP 8 spacecraft. Both the measured IMF direction and its anti-direction are shown for comparison. Solar cosmic ray particles propagate outwards from the sun along IMF lines irrespective of whether the field direction is towards or away from the sun. The derived arrival directions are consistent with this picture. The uncertainties in apparent arrival latitude are expected to be larger than those in longitude since many of the detectors only view equitorially.

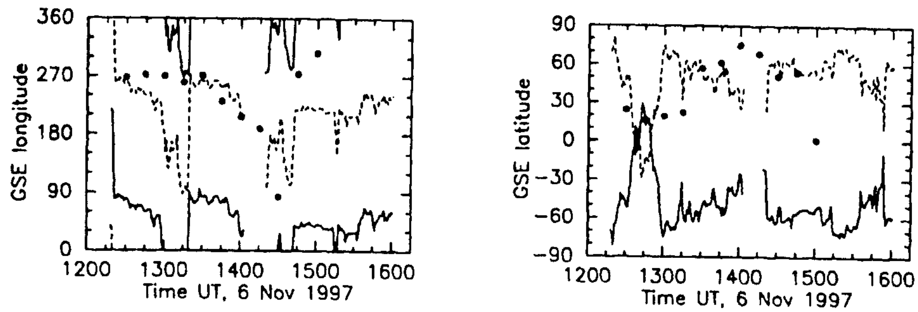

Fig. 4. The measured interplanetary magnetic field directions (solid line) and anti-directions (dashed line). The left panel indicates geocentric solar ecliptic (GSE) longitude; the right panel indicates GSE latitude. The derived particle flow directions are depicted by dots.

It is important to consider whether the scale size of these IMF variations was sufficiently large to affect the path of particles with gyroradii of the order of 0.01 AU. In particular, during the latitude excursion between ~1230 and 1300 UT and longitude excursion between 1255 and 1320 UT the bulk plasma would have moved less than 0.005 AU (the solar wind speed was ~360 km s^{-1}). In this case the particles may arrive from a direction closer to that observed in the more stable field conditions before and after these excursions. Additional work is necessary to interpret these results more fully.

CONCLUSION

The relativistic solar protons associated with the solar activity around noon on 6 November 1997 arrived at Earth along the IMF direction with a mildly anisotropic particle flux distribution which decreased with time. The particle rigidity spectrum in the range 1–5 GV softened from a power law exponent of −5.2 to −7.5 between 1245 and 1500 UT. Even with a rapidly varying IMF, the apparent particle arrival direction is largely consistent with the measured direction of the interplanetary magnetic field.

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